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Video Observations of Marine Gravel Transport

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Abstract

In an analysis of video observations of gravel transport in the West Solent, UK, collective and individual characteristics of 458 'bursts' of bedload have been examined and the transport velocity and distance of 1680 individual particles in a consecutive succession of 'burst events' determined. Infrequent, long duration, high stress events account for 60% of total transport in only 24% of the total time with the mean free path and transport velocity for particles being 0.16 m and 0.22 m/s, respectively. Clear links between intense intermittent turbulence and bedload transport revealed in this study, suggest progress in modelling requires a clearer understanding of near bed flow structure.

Introduction

In studies examining bedload transport, attention has generally focussed on grain and flow parameters governing average transport rates (van Rijn 1986, Yalin 1963). Data to derive and test these expressions have been obtained using a range of laboratory and field techniques including: Bedload traps (Helley and Smith 1971, Tacconi and Billi 1987); fluorescent and radioactive tracers (Heathershaw 1981, Lees 1979); and ripple progression monitoring (Kachel and Sternberg 1971, Wilkinson and others 1984). Generally, these methods yield only time averaged bedload transport data and therefore provide poor resolution of individual or collective grain motion in time and space. As a result, linkages between boundary layer turbulence and sediment dynamics cannot be established in detail.

Although observation and quantitative measurements of bedload transport have been obtained using motion-picture photography or video in laboratory flumes (Abbott and Francis 1977, Grass 1970, Hubbel and others 1986, Nakagawa and others 1980, Parsons 1972) few data exist for bedload in full scale geophysical flows. Several authors have observed bedload in natural rivers and streams (Drake and others 1988; Whiting and others 1985, 1988), yet despite their widespread occurrence in shelf seas, very few detailed data are available for the bedload transport of coarse marine sediments (Hammond and others 1984).

This paper describes and analyses field observations of the entrainment and bedload transport of marine gravel obtained from continuous video records. Both collective, *en masse* intermittent bedload transport events and individual particle dynamics are examined. To aid interpretation of these observations, simultaneous measurements of flow turbulence and bedload transport previously reported (Thorne and others 1989) are briefly referred to here.

Site Description, Instrumentation and Video Analysis

The field observations were carried out in the West Solent, southern England, during 1982 and 1983 at the location shown in Figure 1. Water depth was approximately 20 m with an average mean surface current of 2.3 m/s. Owing to local shelter effects wave activity was negligible during all experimental periods. Bottom sediments consisted of a quartz sand base (median diameter = 400 μm) overlain with angular to subrounded chert gravel (median diameter = 9.0 mm) (inset B, Fig. 1). Side scan sonar showed the immediate study area to be nominally flat with adjacent gravel bedforms (inset A, Fig. 1). Additional site details are given by Langhorne and others (1982, 1986).

Deployed instrumentation consisted of electromag-

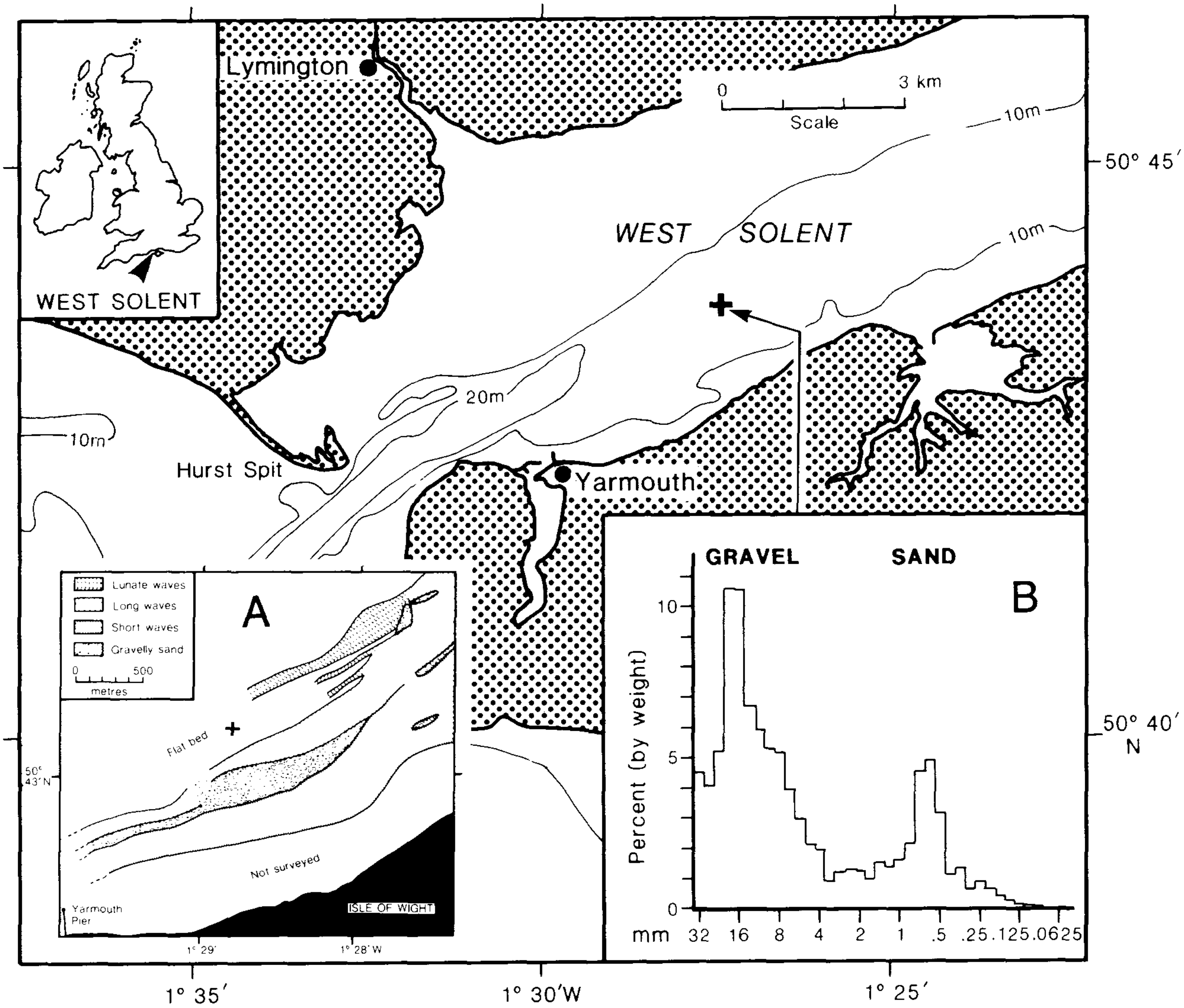

Figure 1. Location of field study site. Insets show: (**A**) prominent gravel bedforms identified from side scan sonar surveys and (**B**) typical grain size distribution obtained from grab samples.

netic current meters to measure the horizontal (u') and vertical (w') component of flow (0.33 m above the bed) and a hydrophone (0.25 m above the bed) to record the sediment generated noise (SGN) that results from interparticle collisions during bedload transport of gravel (Thorne 1986a). Using a detailed calibration procedure involving careful scrutiny of all grain motion during a selected half hour video record, Thorne (1986b) related bedload transport q_b (kg/m/s) to radiated acoustic energy I (μW/m), measured at the hydrophone by

$$q_b = 4.0 \times 10^{-4} I,$$

and showed that this passive acoustic technique could be applied to obtain good estimates of marine gravel transport at sea. During deployment, continuous observations of a 2 m^2 area of sea bed sediments were obtained using a video camera set at an oblique viewing angle 0.5 m above the bed. To overcome the problems associated with image distortion arising from a number of sources, a finely ruled grid was placed on the bottom of a large laboratory tank and the camera set at the field deployment height and view angle. The resulting video image was used to give a scale correction template for use in subsequent determinations of grain size, bedload transport speeds and distances. The diameter of clearly visible surface particles could be estimated to ±0.5 cm and grain transport distance and speed to ±1.0 cm and ±5 cm/s, respectively. Owing to limited resolution, transported particles with an intermediate axis less than 0.5 cm were not considered.

In the following discussion, bedload transport events are defined as being periods of transport lasting at least one second and involving the transport of more than ten particles greater than 1.0 cm in diameter. In the intervening quiescent periods, all grains greater than 2 mm in diameter remained stationary. Selection of video sequences from 1982 and 1983 deployments in which flow and bed conditions were approximately the same (mean current speed at 0.33 m, U_{33} = 1.0 ± 0.1 m/s), permitted the combination of observations in a statistically meaningful way. In total, 458 collective bedload transport events were examined and individual particles moved during a consecutive sequence of 80 events were examined in 1680 cases. Estimates of grain size, transport speed and transport distance obtained by independent observers thoroughly familiar with a given video sequence were rejected if datum differed by more than ±10%.

Results and Discussion

Bedload sediment transport has a multiplicity of forms and regimes dependent principally upon grain size and mean bed shear stress. In the case of marine gravel transport, modes of transport range between an incipient stage of initial particle dislodgement to a sporadic rolling or sliding of grains in response to momentary bed shear stresses in excess of the local threshold. As flow velocity increases further, intervening quiescent periods become shorter and more infrequent. Finally, at very high bed shear stresses, all grains are incorporated in a continuous *en masse* sheet flow sometimes termed a 'traction carpet,' (Postma and others 1988, Todd 1989). It should be noted carefully that at the present site the flow regime falls between these two extremes, with the mean bed shear stress remaining just below the threshold value and giving rise to sporadic bedload transport events in response to momentary excursions of instantaneous bed shear stress above the local threshold value (cf. Thorne and others 1989). Further consideration of bedload transport modes is given below.

Collective Bedload Transport

In Figure 2, visual estimates of bedload transport rate obtained from a typical 30 minute video record (U_{33} = 1.05 m/s) are compared with the SGN measurements from the same period. In Figure 2A, a linear scale of relative transport intensity was devised collectively by observers, with values zero and ten representing no transport and transport of all visible bed material, respectively. In Figure 2B, bedload transport rate measured by the hydrophone has been obtained for the same period. Close correspondence between periods of high and low bedload transport in the example shown in Figures 2A and 2B demonstrates that both the relative magnitude and occurrence of significant transport events have been correctly identified from the video records. In both cases, intermittent bedload transport at this site, typifying the intermediate transport mode, is clearly evident.

In previous studies by Heathershaw and Thorne (1985), turbulent quasi-bursting events, which exhibit similar properties to the turbulent bursting processes observed in the laboratory (cf. Kline and others 1967), have been identified in the present flow data using the quadrature classification scheme (Lu and Willmarth 1973). These studies have shown that sporadic bedload transport events of the type illustrated in Figure 2 are initiated and driven principally by high ephemeral bed shear stresses (frequently 5 to 10 times the mean) which result from an inrush of relatively high velocity fluid towards the bed. In the quadrature scheme, such events are characterised by $u' > 0$, $w' < 0$, where u' and w' are the turbulent fluctuations about the horizontal and vertical mean flow components, U and W, respectively. Such events are considered to be analogous to the sweeps of classical turbulent bursting and together with less frequent events termed 'outward interactions' ($u' > 0$, $w' > 0$) have been found to be highly correlated with the bulk of bedload transport at the present study site. Work by Sutherland (1967), Grass (1970), Utami and Ueno (1987) and Drake and others (1988) has also indicated that similar energetic fluid motions may give rise to and drive a population of mobile bedload grains.

The complex interaction between turbulent flow regimes and sediments such as those described above have been considered by Grass (1970). Grass introduced the novel concept that each individual grain at rest on the bed can be ascribed a unique threshold shear stress value (τ_t). Thus, a natural heterogeneous sediment has a unique threshold probability density function (p.d.f.) determined principally by grain size, shape and placement, $P(\tau_t)$. Similarly, for a given turbulent flow regime, the fluctuating component of instantaneous bed shear stress (τ_i) also has a unique p.d.f., $P(\tau_i)$. Using a simple stochastic model, Grass suggested that the degree of overlap between $P(\tau_t)$ and $P(\tau_i)$ on a common shear stress axis defined, statistically, the mode and rate of sediment transport. This useful conceptual framework is illustrated in Figure 3 which shows varying amounts of overlap between the p.d.f.'s for conditions of: (a) no entrainment; (b) the threshold condition; and (c) conditions of intermittent entrainment and transport. It is considered that a condition similar to that shown in Figure 3c pertains to the present study site during periods of collective grain

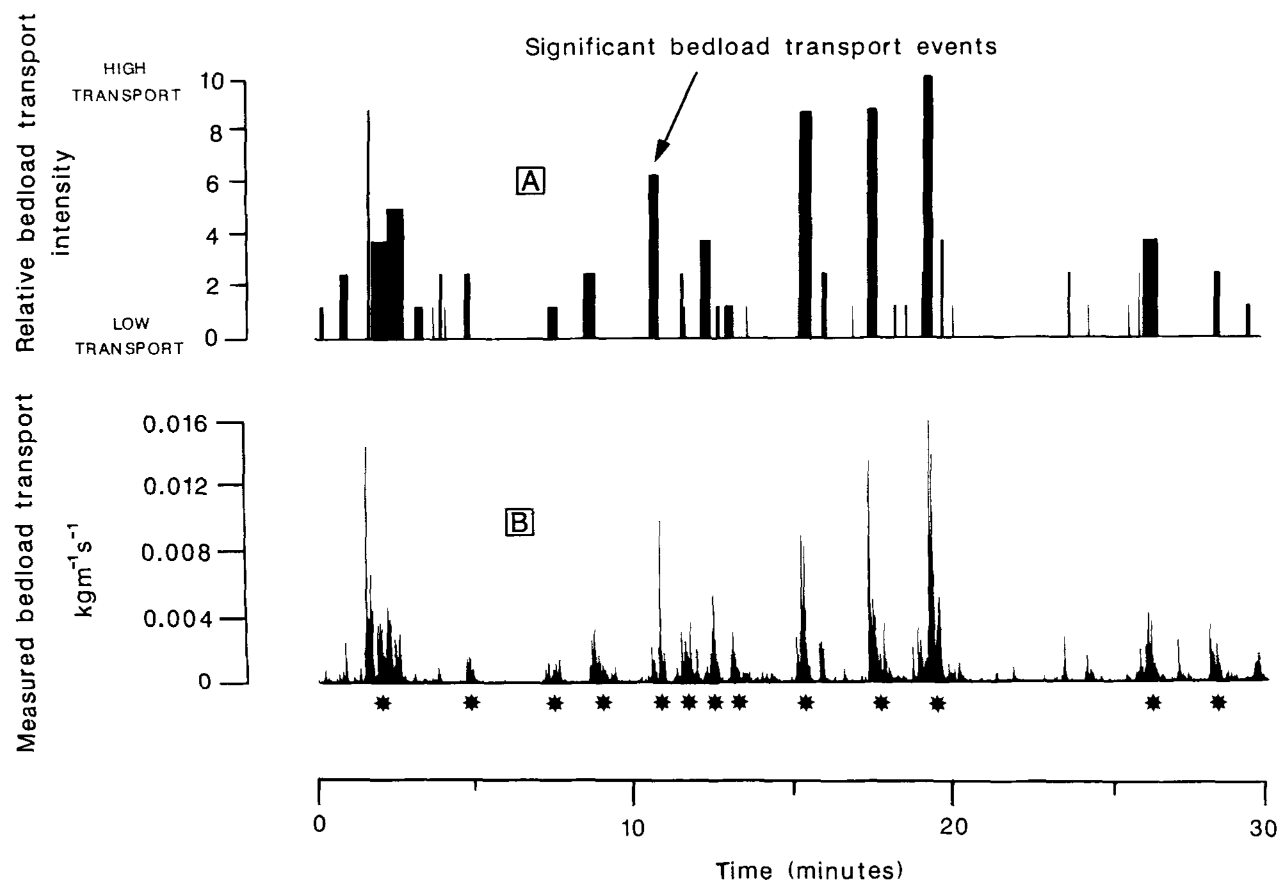

Figure 2. Intermittent nature of marine bedload transport 20:30 hrs, 18 September, 1982: (**A**) visual observations and (**B**) measurements obtained by correlation with acoustic measurements (U_{33} = 1.05 m/s, * = events accounting for more than 60% of the total mass transport).

motion and is probably typical of conditions associated with the majority of moderately mobile marine gravels in shelf seas.

The presence of dispersed fine organic particles in the flow allowed estimation of the flow velocity close to the bed. In common with observations by other workers (Drake and others 1988, Mirtskhulava 1970, Romanofski 1977, Rossinskiy and Lyubomirova 1969), a lag between the relatively slow moving bedload and the significantly faster fluid flow close to the bed was evident during all transport events. While an accurate measurement of the lag was not possible, visual observations indicated that on average bedload moved at approximately half the near bed flow velocity during significant transport events. Owing to the relatively short duration of high bed shear stresses, however, the formation of bedload sheets in flows well in excess of the threshold previously reported by Whiting and other (1985, 1988) and Drake and others (1988) was not observed.

Single Bedload Transport Events

In common with the present observations, several authors (Bridge and Dominic 1984, Meland and Norrman 1966) have reported that, in the intermediate transport mode, the response of sediment to the downstream passage of sweeps is the same regardless of grain properties and exhibits a characteristic sequence of sediment/fluid interactions. In this sequence, the entrainment of grains by fluid drag and lift forces quickly mobilizes the sediment and leads to minor additional entrainment by ballistic impact between the mobile and static grain populations. Contact with the bed, although frequent in the case of large grains is generally brief. The general downstream translocation of all susceptible bed material continues until fluid forces subside to a value below the threshold and motion ceases. A period of bed reorganization lasting 10–20 seconds usually follows a significant transport event (i.e., >0.05 kg/m) in which

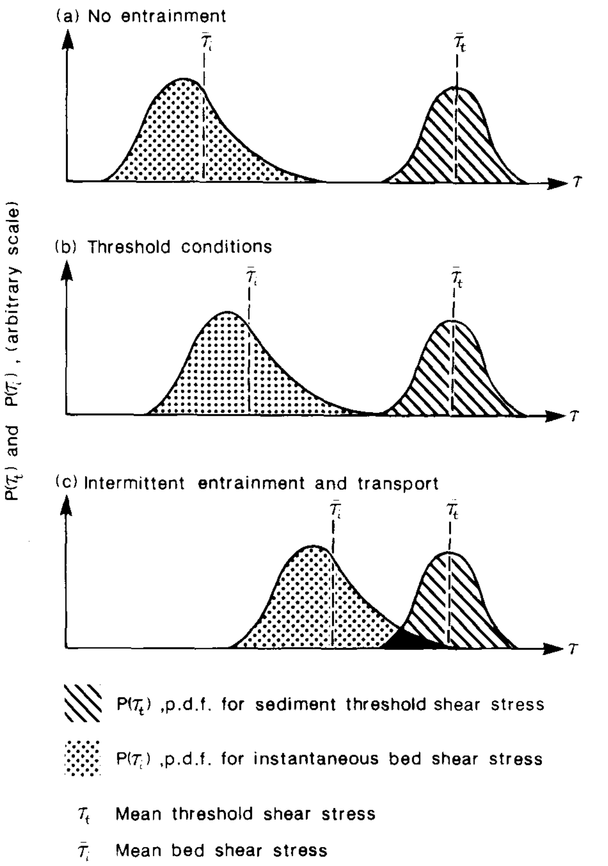

Figure 3. Conceptual stochastic model of bedload transport regimes (after Grass 1970).

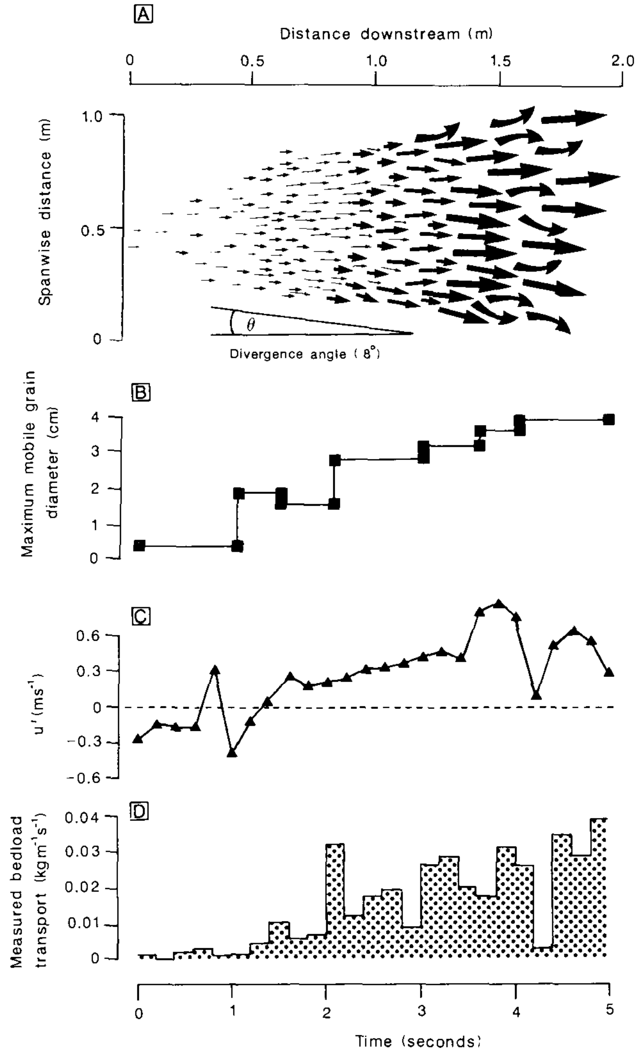

Figure 4. A typical sweep driven bedload transport sequence showing: (**A**) transport pathways and intensity (schematic); (**B**) the increase in mobile grain size; (**C**) u'; and (**D**) mass transport rate with time and distance downstream from the area of initial entrainment.

larger grains perched in precarious positions find more secure resting places and disturbed fine material either settled between coarse grain interstices or is winnowed away. This rapid development of an equilibrium pavement surface appears to be a universal process for natural bimodal or mixed grain size sediments (Andrews and Parker 1987, Bray and Church 1980).

Part of a typical sweep initiated bedload transport sequence from the present study is shown in Figure 4 where concurrent scales of distance and time apply in all cases. In Figure 4A, the average downstream and cross-stream dimensions of the event are shown together with arrows indicating schematically the mean direction of transport. The downstream increase in the size of arrows in this figure reflects an increase in the observed intensity of bedload transport. This cascade of bedload in response to the downstream passage of a sweep event was observed to spread laterally in all cases at a mean divergence angle, θ, of 8° and, as expected in energetic tidal flows, is at a scale far greater than that reported for fluvial bedload transport (Drake and others 1988). Inspection of typical event characteristics at half second intervals shows that once threshold conditions are exceeded, the maximum mobile grain size increases through time (Fig. 4B) and reaches a peak value of 4 cm before the mobile material is swept from the field of view of the camera. In this example, the corresponding 5 Hz records of the horizontal flow component (u') and bedload transport (q_b, obtained acoustically) in Figures 4C and 4D, respectively, show that u' and q_b increases erratically through time during the sweep event. The increase in u' shown here gives rise to an increase in bed shear stress and hence to the application of greater tractive forces on susceptible bed material. As a result, both the amount of transported material and the median grain size of mobile grains increases. These observations conform, therefore, to the generally accepted views of bedload entrainment processes for coarse heterogeneous sediments. Selective entrainment and re-sorting processes reported by Ikeda and Iseya (1988) and Komar and Li (1988) were not evident in any of the *en masse* sweep transport sequences examined in this study despite the relatively wide grain size distribution for this sediment.

Figure 5 shows frequency distributions for mobile grain diameter, transport distance, time and velocity obtained from visual observations of a consecutive sequence of 80 bedload transport events. Observed distributions for the duration and interval between events examined in this study are also shown. In view of the stochastic processes involved in bedload transport, the frequency distributions for transport distance, time and velocity, as expected, deviate significantly from

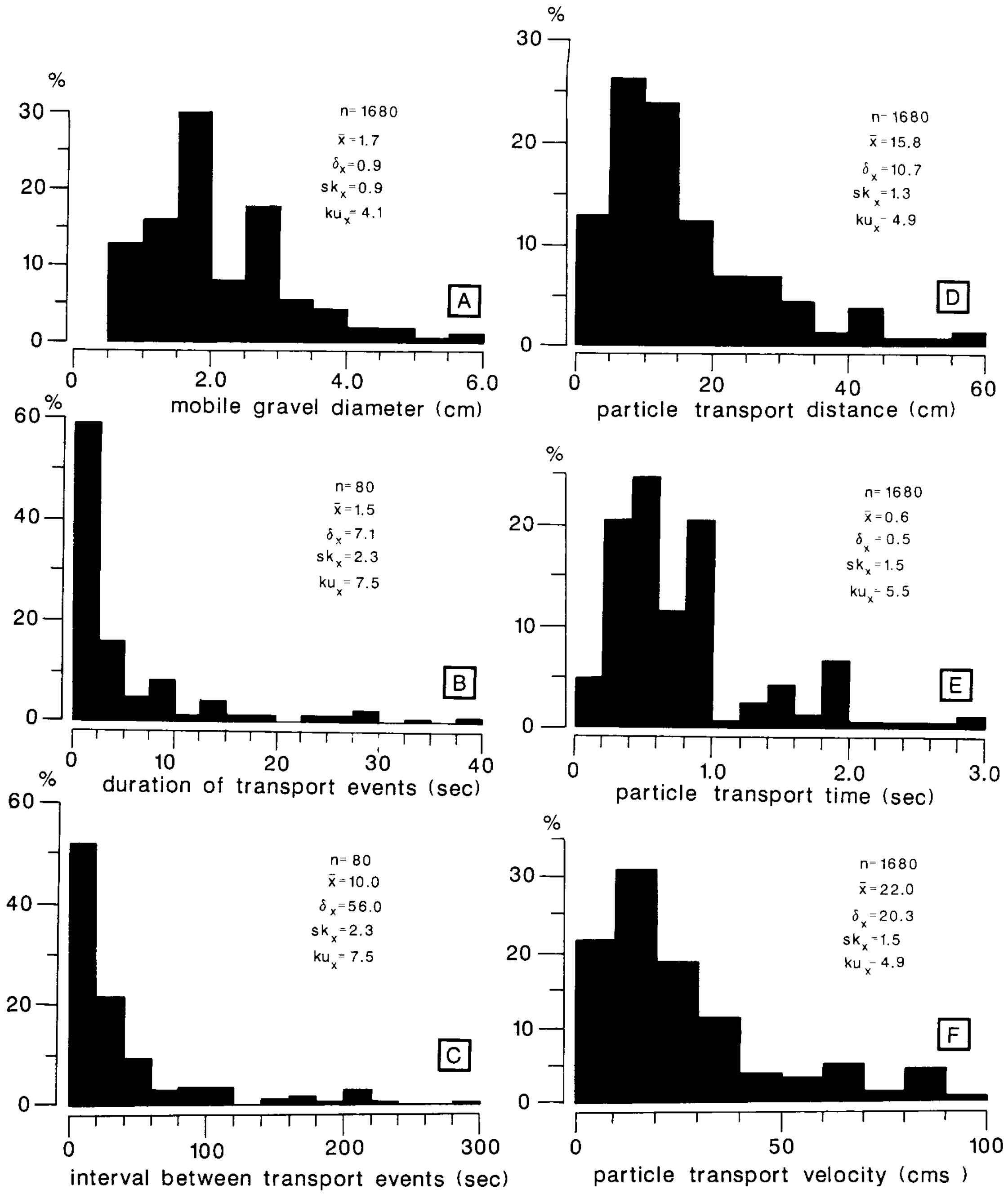

Figure 5. Frequency distribution and statistical characteristics associated with observed bedload transport events and mobile gravel particles (U_{33} = 1.02 m/s): n = number in sample; x = median; σ_x = standard deviation; Sk_x = skewness; ku_x = kurtosis.

Gaussian and to a large extent, reflect the range of grain sizes present in the mobile grain population. Frequency distributions for fine gravel displacement speeds in a small stream obtained by Drake and others (1988) have similar statistical characteristics. No significant correlation between grain size and transport speed or distance was found thus indicating that all grains mobilize during significant transport events. In Figure 5A, the mobile grain size distribution differs significantly from the grab samples (Fig. 1B). Present observations show that approximately 16% of mobile grains exceed the maximum grain size recorded for grab samples (3.2 cm) and indicate that at this site, grab samples do not describe the surficial particles involved in bedload transport well. In such cases, carefully gathered surface sediment samples are probably more representative of the mobile grain population.

The frequency distributions for the duration and interval between events shown in Figures 5B and 5C, respectively, exhibit the high kurtosis values indicative of intermittency (Heathershaw 1979). These data show that bedload transport at this site occurs in frequent, short duration events characterized by a median duration and interval of 1.5 and 10.0 seconds, respectively. To those unfamiliar with marine bedload transport, Figures 5B and 5C may indicate that the bulk of sediment transport is accomplished primarily by these relatively short duration (<10 seconds), high frequency (<50 seconds) events. Recent analysis of the SGN data, however, suggests strongly that while these events give rise to a low magnitude background transport rate (typically <0.02 kg/m), they do not accomplish as much mass transport as the less frequent (>150 seconds), long duration (>20 seconds) events where total mass transport is generally 0.2 to 0.3 kg/m at the present site. Such events are evident in the example shown in Figure 2B where 13 events in a 30 minute SGN record of bedload transport (marked with an asterisk) account for more than 60% of total bedload transport in only 24% of the total time. In view of this, it is considered that further progress in the development of a prognostic stochastic model for bedload transport of marine gravel requires parameterization of duration, interval and magnitude of significant bed shear stress events together with an improved understanding of sediment response to intermittent tractive forces arising during quasi-bursting events.

Conclusions

Data obtained in the present study have shown the value of visual observations in understanding fluid and sediment interactions and have extended the range of grain sizes examined during transport by an energetic, full scale geophysical flow. Bedload transport at the present site is characterized by intense bursts of *en masse* particle motion driven by momentarily high instantaneous bed shear stresses (5–10 times the mean) and separated in time by longer quiescent periods. Previous work has shown such motion to be associated with quasi-fluid bursting processes in the benthic boundary layer. On average, 60% of total bedload is transported during events lasting only 24% of the total time. During such events, grains travel on average at a speed equal to approximately half the near bed flow (0.22 m/s) over distances ≈0.16 m. However, in common with the duration and interval between events, the transport speed and distances associated with the grain population examined were extremely variable.

It is now clear from both past and present work on marine gravel transport that further progress in modelling intermittent bedload requires clearer understanding of boundary layer turbulence structure and of sediment response to the application of momentarily high bed shear stresses. While at present, understanding of the mechanisms governing the interaction between the p.d.f's τ_i and τ_c in the interactive stochastic model proposed by Grass (1970) requires further work, detailed analysis of further data relating to flow and particle motion may prove to be useful in defining *in situ* values for $P(\tau_i)$ and $P(\tau_c)$ for natural sediments. Further work to achieve these objectives using statistical techniques is currently being undertaken.

References

Abbott JE, Francis JRD (1977) Saltation and suspension trajectories of solid grains in a water stream. Proceedings Royal Society, London A284:225–254

Andrews ED, Parker G (1987) Formation of a coarse surface layer as the response to gravel mobility. In: Thorne CR, Bathurst JC, Hey RD (eds) Sediment Transport in Gravel-Bed Rivers. John Wiley & Sons Ltd., pp 269–324

Bray DI, Church M (1980) Armored versus paved gravel beds. Proceedings American Society Civil Engineers, Journal Hydraulic Division 106 (HY11):1939–1940

Bridge JS, Dominic DF (1984) Bedload grain velocities and sediment transport rates. Water Resources Research 20:476–490

Dietrich WE, Smith JD (1984) Bedload transport in a river meander. Water Resources Research 20:1355–1380

Drake TG, Shreve RL, Dietrich WE, Whiting PJ, Leopold LB (1988) Bedload transport of fine gravel observed by motion picture photography. Journal Fluid Mechanics 192:193–218

Francis JRD (1973) Experiments on the motion of solitary grains along the bed of water streams. Proceedings Royal Society London A332:443–471

Grass AJ (1970) Initial instability of fine bed sand. Proceedings American Society Civil Engineers, Journal Hydraulic Division 96 (HY3):619–632

Hammond FDC, Heathershaw AD, Langhorne DN (1984) A comparison between Shields' threshold criterion and the movement of loosely packed gravel in a tidal flow. Sedimentology 31: 51–62

Heathershaw AD (1979) The turbulent structure of the bottom boundary layer in a tidal current. Geophysical Journal of the Royal Astronomical Society 58:395–430

Heathershaw AD (1981) Comparison of measured and predicted sediment transport rates in tidal currents. Marine Geology 42:75–104

Heathershaw AD, Thorne PD (1985) Sea-bed noises reveal role of turbulent bursting phenomenon in sediment transport by tidal currents. Nature 316:339–342

Helley EJ, Smith W (1971) Development and calibration of a pressure-difference bedload sampler. Delft Hydraulics Laboratory, Report R4, 21 pp

Hubbell DW, Stevens HH, Skinner JV, Beverage JP (1986) Laboratory data on coarse sediment transport for bedload sampler calibrations. United States Geological Survey Water Support Paper 2299, 31 pp

Ikeda H, Iseya F (1988) Experimental study of heterogeneous sediment transport. Environment Research Centre Paper, University Tsukuba 12, 50 pp

Kachel NV, Sternberg RW (1971) Transport of bedload on ripples during an ebb current. Marine Geology 10:229–244

Kline SJ, Reynolds WC, Schraub FA, Runstadler PW (1967) The structure of turbulent boundary layers. Journal Fluid Mechanics 30:741–773

Komar PD, Li Z (1988) Applications of grain-pivoting and sliding analyses to selective entrainment of gravel and to flow-competent evaluations. Sedimentology 35:681–694

Langhorne DN, Heathershaw AD, Read AA (1982) The mobility of seabed gravel in the West Solent. Institute of Oceanographic Sciences (UK) Report number 140, 65 pp (unpublished manuscript)

Langhorne DN, Heathershaw AD, Read AA (1986) Gravel bedforms in the West Solent, Southern England. Geo-Marine Letters 5:225–230

Lees BJ (1979) A new technique for injecting fluorescent sand tracer in sediment transport experiments in a shallow water marine environment. Marine Geology 33:M95–M98

Lu SS, Willmarth WW (1973) Measurements of the Reynolds stress in a turbulent boundary layer. Journal Fluid Mechanics 60:481–511

Meland N, Norrman JO (1966) Transport velocities of single particles in bedload motion. Geografiska Annaler Series A42:165–182

Mirtskhulava TY (1970) Investigation of bedload movement by fast microphotography. Izvestiya Akadamia nauk SSSR Series Geography 6:879–881

Nakagawa H, Tsujimoto J, Hosokawa Y (1980) Statistical mechanics of bedload transportation with 16mm film analysis of behaviours of individual sediment particles on a flat bed. Proceedings Third International Symposium on Stochastic Hydraulics August 5–7, 1980, Tokyo, Japan. Japan Society Civil Engineering International Association Hydraulic Research 1: 313–324

Parsons, DA (1972) The speed of sand grains in laminar flow over smooth beds. In: Shen HW (ed) Sedimentation. Fort Collins, Colorado, pp 1-1, 1–25

Postma G, Nemec C, Kleinsphehn K (1988) Large floating clasts in turbidities: a mechanism for their emplacement. Sedimentology Geology 58:47–61

Romanofski VV (1977) Investigation of the speed of bedload movement. Soviet Hydrology 16:108–112

Rossinski KI, Lyubomirova KS (1969) Jump-like movement of a solid particle at the bottom of a turbulent stream. Soviet Hydrology 1:38–49

Sutherland AJ (1967) Proposed mechanism for sediment entrainment by turbulent flows. Journal Geophysical Research 72:6183–6194

Tacconi P, Billi P (1987) Bedload transport measurement by the vortex trap on Virginio Creek, Italy. In: Thorne CR, Bathurst JC, Hey RD (eds) Sediment Transport in Gravel Bed Rivers. John Wiley & Sons Ltd., pp 583–616

Thorne PD (1986a) Laboratory and marine measurements on the acoustic detection of sediment transport. Journal Acoustic Society America 80:899–910

Thorne PD (1986b) An intercomparison between visual and acoustic detection of seabed gravel movement. Marine Geology 72: 11–31

Thorne PD, Williams JJ, Heathershaw AD (1989) In situ acoustic measurements of marine gravel threshold and transport. Sedimentology 36:61–74

Todd SP (1989) Stream-driven, high density gravelly traction carpets: possible deposits in the Trabeg Conglomerate formation, SW Ireland and some theoretical considerations of their origin. Sedimentology 36:513–530

Utami T, Ueno T (1987) Experimental study on the coherent structure of turbulent open channel flow using visualisation and picture processing. Journal Fluid Mechanics 174:399–440

Van Rijn LC (1986) Applications of sediment pick-up function. Journal Hydraulic Engineering American Society Civil Engineers 112(9):867–874

Whiting PJ, Dietrich WE, Leopold LB, Collins L (1985) The variability of sediment transport in a fine-gravel stream (abstract). Publication Third International Fluvial Sedimentology Conference August 7–9, 1985. Fort Collins, Colorado, pp 38

Whiting PJ, Dietrich WE, Leopold LB, Drake TG, Shreve RL (1988) Bedload sheets in heterogeneous sediments. Geology 16(2):105–108

Wilkinson RH, Salkield AP, Moore EJ (1984) Photogrammetry in sediment studies. In: D George (ed) Underwater Photogrammetry and Television for Scientists. Clarendon Press, Oxford, pp 000

Williams JJ, Thorne PD, Heathershaw AD (1989a) Measurements of turbulence in the benthic boundary layer over a gravel bed. Sedimentology 36:959–971

Williams JJ, Thorne PD, Heathershaw AD (1989b) Comparison between acoustic measurements and predictions of the bedload transport of marine gravels. Sedimentology 36:973–979

Yalin MS (1963) An expression for bedload transportation. Journal Hydraulic Division American Society Civil Engineers 89(HY3):221–250

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